Distributed Slack Bus Model for Qualitative Economic Load Dispatch

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Distributed Slack Bus Model for Qualitative Economic Load Dispatch

A thesis submitted in partial accomplishment of the requisites for the degree of ***Bachelor of Technology*** *in* ***Electrical Engineering***

By

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CERTIFICATE

This is to certify that the thesis titled "**Distributed Slack Bus Model for Qualitative Economic Load Dispatch**", submitted to the National Institute of Technology, Rourkela by **Mr. Soumya Ranjan Panda,Roll No**: **109EE0292** for the award of **Bachelor of Technology**in Electrical Engineering, is a bona fide record of research work carried out by him under my supervision and guidance.

The candidate has fulfilled all the prescribed requirements.

The thesis, which is based on candidate's own work,has not been submitted elsewhere for a degree/diploma.

In my opinion, this thesis is of standard required for the award of a **Bachelor of Technology**in Electrical Engineering.

Signature of student

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I prolong my appreciation to the researchers and engineers whose hours of work has produced thepapers and theses that I have employed in my project.

Soumya Ranjan Panda

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Dedicated
To
My Parents

ABSTRACT

The power flow analysis in a highly interconnected grid is a big problem for an electrical engineer. The next big obstacle is that of Economic Dispatch at the load side. The issue with Economic Load Dispatch (ELD) is with allocating the total generation to the individual generators in such a way that the total cost of generation at any time is at a minimum. In this project, the optimal cost of generation has been analyzed with a distributed slack bus model. In ordinary load flow method, the slack bus is bound to carry the entire extra burden of the system. In the proposed technique, the burden on slack bus shall be reduced and still maintain the equal incremental cost criteria. A new term called Participation factor shall be utilized to achieve the same as the total loss of the system at the end of iteration shall get distributed among all the generating units. Finally practical bus network problems shall be taken as case study and results shall be analyzed and compared with the existing ELD scheme to verify the usefulness of the proposed technique.

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OBJECTIVE

To studythe effect of distributing the burden on the slack busmaking use ofEconomic LoadDispatchincluding transmission losses and compare the results with the results of existing ELD schemes using IEEE 30 bus system.

Chapter 1

Introduction

1. INTRODUCTION

Distributed generation has been growing rapidly in power systems. Previously, one dominant source, the substation, existed in distribution systems. Now, the consistent supply of energy from DGs, the number of sources and the percentage of real power injections from DGs have significantly increased. This has resulted in more complex power systems and thus increasing the complexity of its analysis.

The power flow analysis is an essential and fundamental tool to power systems engineers. However, the conventional power flow analysis has at least two drawbacks due to the very existence of the slack bus. First, 'only one slack bus' assumption is unrealistic in which all losses in a power system are given to only one slack bus. No such situation happens in the operations of power systems. Second, the 'equal incremental cost' which is deduced from the economic load dispatch (ELD) is not maintained after the power flow calculation because of the slack bus whose amount of generationis determined after the power flow calculation. Moreover, as the electricity market is more and more deregulated, the idea that some specified groups of generators play the role in slack buses looks inappropriate. The technique of removing the concentrated burden of the slack bus is considered in the way of distributing all losses to each generator bus in a power system.

There are different methods to distribute the burden on the Slack Bus and the one used here is considering Economic Load Dispatch.

1.1 LOAD FLOW STUDIES

In power engineering, the power flow study, also known as load-flow study, is a significant tool involving mathematical analysis applied to anintegrated power system. A power flow study normally uses simplified notations such as one-line diagram and per-unit system, and does focus on various forms of AC power (i.e.: voltages, voltage angles, real power and reactive power). It analyzes the power system in normal steady-state operation. Many software implementations of power flow studies exist.

Power flow or load flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. The main information obtained from the power flow study is the magnitude and the phase angle of the voltage at each and every bus, and the active and reactive power flowing in each transmission line.

The goal of a power flow study is to acquire complete voltage angle and magnitude info for each bus in a power system for specific load and generator real power and voltage conditions. Once this information is acquired, real and reactive power flow in each branch as well as generator reactive power output can be determined. Due to the nonlinear nature of this problem, following numerical methods as in [1] are used to obtain a solution that is within an acceptable tolerance-

1. Gauss-Seidel Method
2. Newton-Raphson Method
3. Fast Decoupled Method

Out of these 3 methods NR method is considered to be the best method and thus will be used in this project in later phase.

1.2 BUS CLASSIFICATION

With each bus in the power system assigned with a real power, active power, voltage magnitude and phase angle value, the buses can be classified into three categories according to quantities specified at each bus.

Bus Type	**Quantities Specified**	**Quantities to be Obtained**
Load Bus	P, Q	$\lvert V \rvert$, δ
Generator Bus	P, $\lvert V \rvert$	Q, δ
Slack Bus	$\lvert V \rvert$, δ	P, Q

Table 1.1 Bus Classification in Power System

Load Buses:

In these buses no generator units are connected and hence the generated real power and reactive power are taken to be zero. The power taken by these buses are defined by real power and reactive power in which the negative sign denotes the power flowing out of the bus. So, these buses are sometimes referred to as P-Q bus. The objective of the load flow is to find the bus voltage magnitude $\lvert V_i \rvert$ and its angle δ_i.

Voltage Controlled Buses/Generator Buses:

These are the buses where generating units are connected. Therefore the power generation in these buses is controlled through a prime mover while the terminal voltage is controlled through the generator field excitation. The input power is maintainedconstant through turbine-governor control and the bus voltage is kept constant by making use automatic voltage regulator. So, such buses are also referred to as P-V buses. It is to be noticed that the reactive power supplied by the generator depends on the system parameters and cannot be specified in advance. Now we have to find the unknown angle δ_i of the bus voltage.

Slack or Swing Bus:

Usually this bus is numbered as bus 1 for the load flow studies. This bus sets the angle reference for all other buses. Since it is the angle difference between the two voltage sources that decides the real and reactive power flow among them, thebus voltage angle of the slack bus is not important. However it sets the reference according to which angles of all the other bus voltages are analyzed. For this reason the voltage angle of this bus is usually chosen as 0°. Now it is assumed that magnitude of the voltage of this bus is known or set. [1]

1.3 ECONOMIC LOAD DISPATCH

Economic Load Dispatch (ELD) is based upon two things. Firstly, the generating units must provide for the power required in the load side by optimally using the units. Secondly, the units must be ready to provide a backup, although within a limit, if other units fail to generate.

The first aspect is largely necessary since with the increase in dimension of the grid and integrity the losses increase. Hence meeting the power requirements cannot be done just based on availability of generating units. It mayhappen that the power generating cost at Station A is less than that of Station B. Naturally; the power requirement must be supplied by Station A because it is less costly. But if Station A is far away from the load location as compared to Station B, it might not be optimal to do the same because of the transmission losses. There are many constraints to look upon before deciding on which generating unit will generate how much.

Finally, the ELD scheme searches for a load flow solution out of many which optimally satisfies all the technical and most of the economic constraints of the power system. Since total cost of generation is a function of individual production of the generating units, the system constraints will decide the total cost of the system.

System Constraints in ELD:

There are two types of constraints:

(i) Equality constraints

(ii) Inequality Constraints

1.4 BURDEN ON SLACK BUS

The slack bus accountsfor two functions in a load flow. It can serve as a virtual reference for other buses in the system with its phase being assigned as zero. The second purpose is of acting as a source (as well as sink) for the unaccounted active and reactive power, which is the system loss. In a system where the incremental fuel cost has to be kept equal on all buses, by asking one bus to carry all the extra burden, this idea iscertainly violated [2]. Thus the existing optimum solution is not optimum at all for the slack bus. In the previous ELD schemes, nothing can be done about it, because the insertion of slack bus in the jacobian matrix will make it singular and the solution will fail.

Thus the idea is of distributing the burden on the slack bus to other generator buses in the system in order to increase the quality of Economic Load Dispatch.

1.5 DISTRIBUTED SLACK BUS

To distribute the burden on the slack bus among other voltage controlled buses a constraint named as Participation Factor [3] is introduced into the existing ELD method.A participation factor is a simple algebraic ratio. It is thefactor attached to each generator bus such that, the total unaccounted or loss power shall be distributed to that bus multiplied by that factor.

According to the participation factor allotted to each bus the burden or loss is distributed among them.Detailed study of this process and comparing the results with the existing ELD scheme results is the main aim of the project.

Chapter 2

Economic Load Dispatch

2. ECONOMIC LOAD DISPATCH

2.1 EQUALITY CONSTRAINTS

These are the basic load flow equations, given by:

$$P_p = \sum_{q=1}^{n}\{e_p(e_q G_{pq} + f_q B_{pq}) + f_p(f_p B_{pq} - e_q B_{pq})\} \tag{2.1}$$

$$Q_p = \sum_{q=1}^{n}\{f_p(e_q G_{pq} + f_q B_{pq}) - e_p(f_p B_{pq} - e_q B_{pq})\} \tag{2.2}$$

p = 1,2,3,…,n.

where e_p and f_p are real and imaginary parts of voltage at the p^{th} node and G_{pq} and B_{pq} are the conductance and susceptance between the p^{th} and the q^{th} nodes. [1]

2.2 INEQUALITY CONSTRAINTS

a) Generator Constraints-

The kVA loading on a generator is given by $\sqrt{P_p^2 + Q_p^2}$ and this should not exceed a pre-decided value C_p because of the temperature rise condition that is $P_p^2 + Q_p^2 \leq C_p^2$. If the power output of a generating unit for optimum performance of the system is less than a pre-assigned value P_{min}, the unit is not connected to the bus bar because it is not possible to generate such low value of power from that unit. Hence the generated power P_p cannot be taken outside the range given by the inequality $P_{pmin} \leq P_p \leq P_{pmax}$. Similarly, the maximum and minimum reactive power that can be generated by a source is limited. Hence the generator reactive power Q_p cannot be taken outside the range as stated by the inequality i.e. $Q_{pmin} \leq Q_p \leq Q_{pmax}$.

b) Voltage Constraints-

It is needed that the voltage magnitudes and phase angles at each node should vary within a certain range. The voltage magnitude should vary within a certain range otherwise most of the equipment connected to the system would not operate as needed or additional use of voltage regulating device would make the system non-economical. Thus $|V_{min}| \leq |V_p| \leq |V_{max}|\ and\ \delta_{pmin} \leq \delta_p \leq \delta_{pmax}$ where V_p and δ_p stand for the voltage magnitude and phase angle at the p^{th} bus or node. Normally operating angle of transmission line lies between 300 and 450 for transient stability considerations. Therefore a higher limit is set on angle δ. A lower limit of δ assures proper usage of transmission facility.

c) Running Spare Capacity Constraints-

These constraints are required to meet:

(i) The forced outages or cutoff of one or more alternators on the system

(ii) The unexpected extra load on the system

The load generation should be such that in addition to load demand and system losses a minimum spare capacity must be available i.e.

$$G \geq P_D + P_L$$

$$or\ \ G = P_D + P_L + P_{SO}$$

where G is the total the generation capacity and P_{SO} is some pre-assigned power. A well planned system is the one in which spare capacity P_{SO} is minimum.

d) Transformer Tap Settings-

If an auto transformer is used, the minimum tap setting could be 0 and the maximum could be 1 i.e. $0 \leq t \leq 1$. Similarly for a two winding transformer if tappings are provided on the secondary side$0 \leq t \leq n$, where n is the transformer ratio. Phase shift limits of the phase shifting transformer is given by,

$\theta_{pmin} \leq \theta_p \leq \theta_{pmax}$.

e) Transmission Line Constraints-

The flow of real and reactive power through the transmission line is limited by the thermal stability of the line and is expressed as$C_p \leq C_{pmax}$, where C_{pmax} is the maximum loading capacity of the p^{th} line.

f) Network Security Constraints-

If initially a system is operating under satisfactoryconditions and there is an outage, may be forced or faulty one, it is normal that some of the constraints of the system will be violated. The complexity of these constraints is increased when a largeintegrated system is under observation. In this case an analysis is to be done with outage of one branch at a time and then more branches at a time. The nature of these constraints is same as voltage and transmission line constraints. [1]

2.3 METHODS OF SOLVING ELD PROBLEMS

The solution of the ELD problem basically depends on the equal incremental cost for each generator. The cost curves are analyzed to arrive at the equal cost scenario. If the distances involved in the grid are short, then the transmission losses can be neglected entirely. Thus the ELD scheme becomes like,

$$\text{Min } F_T = \sum_{n=1}^{n} F_n \tag{2.3}$$

$$\text{Subject to} P_D = \sum_{n=1}^{n} P_n \tag{2.4}$$

where, F_T is total fuel input to the system, F_n is the fuel input to the n^{th} generating unit, P_D is the total load demand and P_n the generated power of n^{th} unit. By making use of a Lagrangian multiplier technique [1], we reach at a solution where,

$$\frac{dF_1}{dP_1} = \frac{dF_2}{dP_2} = \frac{dF_3}{dP_3} = \cdots = \frac{dF_n}{dP_n} \tag{2.5}$$

Here $\frac{dF_1}{dP_1}$is the incremental cost of generation at plant 1 in terms of unit currency/hr and so on.

But in actual scenario, we cannot neglect the transmission losses and hence they do play a part in ELD analysis [1]. With the losses in the picture, the new scheme becomes that of,

$$\text{min} F_T = \sum_{n=1}^{n} F_n$$

$$\text{subject to} P_D + P_L = \sum_{n=1}^{n} P_n \tag{2.6}$$

where P_L is the total system loss which is assumed to be a function of generation and the other terms have their usual significance. Solving this using the Lagrangian multiplier again, we arrive at,

$$P_n = \frac{1 - \frac{f_n}{\lambda} - \sum_{m \neq n} 2B_{mn}P_m}{\frac{F_{nn}}{\lambda} + B_{nn}} \tag{2.7}$$

With a certain coordination equation written as,

$$F_{nn}P_n + f_n + \lambda \sum_{m \neq n} 2B_{mn}P_m = \lambda \tag{2.8}$$

The simultaneous equations derived are then solved using standard matrix inversion routine or by using any iterative procedure. Another technique of solving the ELD problem is named as the modified coordination equation method which uses the technique of changing the bus power of one plant by small amounts keeping the other end of bus voltage constant [1]. This incremental change brings about some stable changes in the grid in long run. In this method, Pi is positive for generator and negative for load bus,

$$\therefore dP_L = \sum_{i=1}^{n} \frac{\partial P_L}{\partial P_i} dP_i \tag{2.9}$$

In an interconnected system, if we vary the power P_j with respect to P_n in small amounts, we get,

$$dP_{Lj,n} = \frac{\partial P_L}{\partial P_j} dP_j + \frac{\partial P_L}{\partial P_n} dP_n \tag{2.10}$$

Further solving the equation we come to a new set of equations known as the Modified Coordination Equations (where n^{th} bus is the reference bus)-

$$\frac{dF_n}{dP_n} = \frac{dF_j}{dP_j} \frac{1}{\left(1 - \frac{dP_{Lj,n}}{dP_j}\right)} = \mu \tag{2.11}$$

where μ is the modified incremental cost of received power.

2.4 ALGORITHM FOR SOLVING ELD PROBLEM INCLUDING TRANSMISSION LOSSES

1. Assume a suitable value of λ^0. This value should be more than the largest intercept of the incremental production cost,found from the curve, of the various generators.
2. Calculate the generated powers based on equal incremental production cost.
3. Calculate the generated power at all buses using the equation no. (2.7)-

$$P_n = \frac{1 - \frac{f_n}{\lambda} - \sum_{m \neq n} 2B_{mn}P_m}{\frac{F_{nn}}{\lambda} + B_{nn}}$$

It is to be noted that the powers to be used on the right hand side during zeroth iteration point to the values calculated in step 2. For subsequent iterations the values of powers to be used corresponding to the powers is calculated in the previous iteration. In a case, when the generations violate the limit,the generation of that generating unit is fixed at the limit violated.

4. Check if the difference in power at all generator buses between two consecutive iterations is less than a pre-specified value taken as small as possible. If not, go back to step 3.
5. Calculate the losses using the following relation

$$P_L = \sum_m \sum_n P_n B_{mn} P_m \quad (2.12)$$

and calculate

$$\Delta P = |\sum P_G - P_L - P_D| \quad (2.13)$$

6. If ΔP is less than ϵ, stop calculation and calculate the cost of generation with these values of powers.
7. Update the value of λ and go back to step 3.

Chapter 3

Participation Factor Studies

3. PARTICIPATION FACTOR STUDIES

3.1 TYPES OF PARTICIPATION FACTORS

A Participation factor is the weight assigned to each generator bus or PV bus such as to take care of the burden of the slack bus accordingly. It may be calculated in 2 ways viz.

i. network sensitivity participation factors
ii. generator domain participation factors

The network sensitivity participation factors include penalty factor and network sensitivities for the distribution of the slack bus. Penalty factors can be applied as follows-

$$K_i = \frac{L_i P_{Gi}^{load}}{\sum_{j=1}^{m} L_i P_{Gi}^{load}} \qquad i=1, 2\ldots m \tag{3.1}$$

as j changes at each iteration $L_i$and the participationfactors are iterative.

The generator domains try to incorporate a set of buses and branches and their power flows to specific participating generators.The effectsof network parameters, generator capacities and load distributions are explicitly used in these participation factors.

Thegenerator domain participation factors are as follows:

$$K_i = \frac{P_{Gi}^{loss}}{P_{Loss}} \qquad i=1, 2\ldots m \tag{3.2}$$

where P_{Loss} is the total line loss of all the buses.

In the distributed slack bus model, the real power outputs of generating sources are iterative. Generator domains and loss contributions change with varying source inputs. Thus, theparticipation factors are iterative during power flow numerical analysis. [3]

In this project the participation factor used is

$$K_i = \frac{P_{Gmi}}{\sum_{j=1}^{m} P_{Gmi}} \qquad i=1, 2\ldots m \tag{3.3}$$

where P_{Gmi} is the minimum power generation limit of i^{th} PV bus.

3.2 IMPLEMENTATION OFPARTICIPATION FACTOR

At the completion of the iteration, the load flow generates the active power of the generators individually in the power system. This value is analyzed keeping the ELD scheme in mind. Now the generating unit is most economical and optimal for this value of active power and not its presumed capacity at the start of iteration. Thus, we can say that the economical nature of generation is maintained about this value at that instant.

By taking into account this K_i value, the expressions and equations change. Now the active power at each PV bus is,

$$P_{Gi} = P_{Gi\_scheduled} + K_i P_{loss} \tag{3.4}$$

Now the reactive power expression remains the same. The ELD scheme can be described as:

$$\text{Min} \sum_{i=1}^{m} C_i P_{Gi} \tag{3.5}$$

$$\text{Subject to} \sum_{i=1}^{m} P_{Gi} - P_{load} - \Delta P_B \tag{3.6}$$

where ΔP_B is the term due participation factor K_i. [2]

Now let's see what happens to the Newton-Raphson matrix (Jacobian matrix).

The jacobian matrix that was taken in conventional load flow algorithm did not consider the slack bus as a PV bus. And the standard jacobian matrix equation was,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{3.7}$$

where Jn denotes a jacobian sub-matrix for any given system, ΔP and ΔQ are the changes in real and reactive power respectively for the given system and Δδ and Δ|V| are the changes in phase angle and voltage magnitude at the given node. The size of the jacobian is decided according to the number of PV buses in the total number of buses using two equations, viz.

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{3.8}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{3.9}$$

where $|V_i|$,$|V_j|$ are the bus voltage magnitudes, Y_{ij} is the line admittance of the i-j branch, θ_{ij} is the difference in phase angle at the two ends of the i-j branch, and δ_i, δ_j are the phase angles of the i^{th} and j^{th} PV buses.

For each generator bus which is voltage dependent, the active power equation is valid only. For every PQ bus, both the active and reactive power equations are valid. Thus, if there are in total n number of buses and m number of PV buses, then there shall be (n-1) number of real equations and (n-m-1) number of reactive power equations. Since the slack bus is not considered the size of the Jacobian matrix is therefore (2n-m-2) x (2n-m-2).

In the new model, the slack bus shall be included in the jacobian matrix and a new term P_B shall be mentioned in the active power equation. Then the NR matrix is modified. But as we see, adding a column in the jacobian matrix changes the dimensions of the resultant matrix. So we shall include a term in the Δδ, |V| column matrix to balance the matrix dimension.The new term is added to the Δδ |V| column matrix as ΔP_B which is the change in the power generation at every PV bus with respect to the respective K_i value. Now, the new jacobian matrix equation as in [4] looks like,

$$\begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_n \\ \Delta Q_1 \\ \vdots \\ \Delta Q_{n-m} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_n} & \frac{\partial P_1}{\partial |V|_1} & \cdots & \frac{\partial P_1}{\partial |V|_{n-m}} & K_i \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial P_n}{\partial \delta_1} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |V|_1} & \cdots & \frac{\partial P_n}{\partial |V|_{n-m}} & K_n \\ \frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_n} & \frac{\partial Q_n}{\partial |V|_1} & \cdots & \frac{\partial Q_n}{\partial |V|_{n-m}} & \frac{\partial Q_1}{\partial P_B} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial Q_{n-m}}{\partial \delta_1} & \cdots & \frac{\partial Q_{n-m}}{\partial \delta_n} & \frac{\partial Q_{n-m}}{\partial |V|_1} & \cdots & \frac{\partial Q_{n-m}}{\partial |V|_{n-m}} & \frac{\partial Q_{n-m}}{\partial P_B} \end{bmatrix} \begin{bmatrix} \Delta \theta_1 \\ \vdots \\ \Delta \theta_n \\ \Delta |V|_1 \\ \vdots \\ \Delta |V|_{n-m} \\ \Delta P_B \end{bmatrix} \tag{3.10}$$

Now looking at the modified jacobian matrix and its corresponding output matrix, we can deduce that the load flow solution considering this new matrix equation will be different from normal ELD scheme.

Let's look briefly what we have done to the new column of the jacobian matrix.

For generator buses,

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos\left(\theta_{ij} - \delta_i + \delta_j\right) + K_i P_B \tag{3.11}$$

$$\frac{\partial P_i}{\partial P_B} = K_i \tag{3.12}$$

For load buses the extra term $K_i P_B$ is not there so,

$$\frac{\partial P_i}{\partial P_B} = 0 \tag{3.13}$$

And now the reactive power equations from (3.9),

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin\left(\theta_{ij} - \delta_i + \delta_j\right)$$

$$\frac{\partial Q_i}{\partial P_B} = 0 \tag{3.14}$$

The new Jacobian matrix now looks as,

$$\begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_n \\ \Delta Q_1 \\ \vdots \\ \Delta Q_{n-m} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_n} & \frac{\partial P_1}{\partial |V|_1} & \cdots & \frac{\partial P_1}{\partial |V|_{n-m}} & K_i \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & K_m \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_n}{\partial \delta_1} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |V|_1} & \cdots & \frac{\partial P_n}{\partial |V|_{n-m}} & 0 \\ \frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_n} & \frac{\partial Q_n}{\partial |V|_1} & \cdots & \frac{\partial Q_n}{\partial |V|_{n-m}} & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial Q_{n-m}}{\partial \delta_1} & \cdots & \frac{\partial Q_{n-m}}{\partial \delta_n} & \frac{\partial Q_{n-m}}{\partial |V|_1} & \cdots & \frac{\partial Q_{n-m}}{\partial |V|_{n-m}} & 0 \end{bmatrix} \begin{bmatrix} \Delta\theta_1 \\ \vdots \\ \Delta\theta_n \\ \Delta |V|_1 \\ \vdots \\ \Delta |V|_{n-m} \\ \Delta P_B \end{bmatrix} \tag{3.15}$$

Now this matrix equation is used to find out the optimum load flow solution along with the conventional methods and the results are compared.

In this project the IEEE 30 bus system is being considered and analyzed.

Chapter 4

Case Study and Results

4. CASE STUDY AND RESULTS

4.1 STUDY OF THE IEEE 30 BUS SYSTEM

The load flow algorithm was implemented on the system using a MATLAB code [5]. The input was given using the IEEE 30 bus system[6]. Three different codes or algorithms wereapplied on the input bus system, viz.

1. Ordinary Newton Raphson Load flow.

2. Ordinary Newton Raphson Load flow followed by ELD analysis using Coordination equations.

3. Distributed slack bus model using ELD analysis.

4.2 SINGLE LINE DIAGRAM

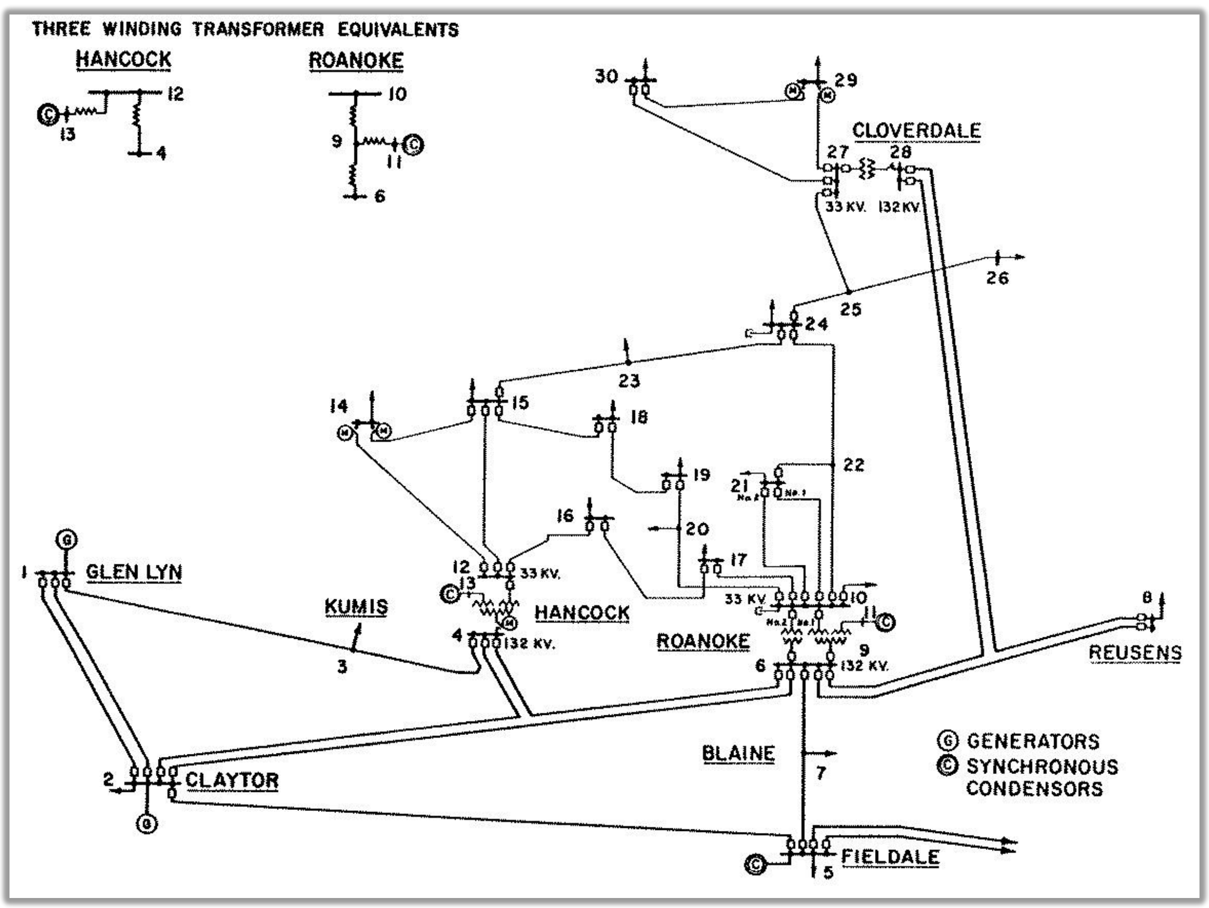

Figure 4.1 IEEE 30 bus system- Single line diagram

4.3 MATLAB INPUT DATA

```
Command Window
File  Edit  Debug  Desktop  Window  Help
>> %              |Bus | Type | Vsp | theta | PGi | QGi | PLi | QLi |  Qmin | Qmax |
busdat30 = [1       1    1.06    0        0     0     0     0     0        0;
            2       2    1.043   0       70  50.0  21.7  12.7   -40       50;
            3       0    1.0     0        0     0   2.4   1.2     0        0;
            4       0    1.06    0        0     0   7.6   1.6     0        0;
            5       2    1.01    0       45  37.0  64.2  19.0   -40       40;
            6       0    1.0     0        0     0   0.0   0.0     0        0;
            7       0    1.0     0        0     0  22.8  10.9     0        0;
            8       2    1.01    0       25  37.3  30.0  20.0   -10       40;
            9       0    1.0     0        0     0   0.0   0.0     0        0;
           10       0    1.0     0        0     0   5.8   2.0     0        0;
           11       2    1.082   0       25  16.2   0.0   0.0    -6       20;
           12       0    1.0     0        0     0  11.2   7.5     0        0;
           13       2    1.071   0       35  20.6   0.0   0.0    -6       24;
           14       0    1.0     0        0     0   6.2   1.6     0        0;
           15       0    1.0     0        0     0   8.2   2.5     0        0;
           16       0    1.0     0        0     0   3.5   1.8     0        0;
           17       0    1.0     0        0     0   9.0   5.8     0        0;
           18       0    1.0     0        0     0   3.2   0.9     0        0;
           19       0    1.0     0        0     0   9.5   3.4     0        0;
           20       0    1.0     0        0     0   2.2   0.7     0        0;
           21       0    1.0     0        0     0  17.5  11.2     0        0;
           22       0    1.0     0        0     0   0.0   0.0     0        0;
           23       0    1.0     0        0     0   3.2   1.6     0        0;
           24       0    1.0     0        0     0   8.7   6.7     0        0;
           25       0    1.0     0        0     0   0.0   0.0     0        0;
           26       0    1.0     0        0     0   3.5   2.3     0        0;
           27       0    1.0     0        0     0   0.0   0.0     0        0;
           28       0    1.0     0        0     0   0.0   0.0     0        0;
           29       0    1.0     0        0     0   2.4   0.9     0        0;
           30       0    1.0     0        0     0  10.6   1.9     0        0]
OVR
```

Table 4.1 Bus data input

```
>> %          |  From |  To    |    R      |    X      |     B/2   |  X'mer  |
%         |  Bus   | Bus    |  pu      |  pu       |     pu    | TAP (a) |
linedat30 = [1      2       0.0192    0.0575     0.0264         1
             1      3       0.0452    0.1652     0.0204         1
             2      4       0.0570    0.1737     0.0184         1
             3      4       0.0132    0.0379     0.0042         1
             2      5       0.0472    0.1983     0.0209         1
             2      6       0.0581    0.1763     0.0187         1
             4      6       0.0119    0.0414     0.0045         1
             5      7       0.0460    0.1160     0.0102         1
             6      7       0.0267    0.0820     0.0085         1
             6      8       0.0120    0.0420     0.0045         1
             6      9       0.0       0.2080     0.0         0.978
             6     10       0.0       0.5560     0.0         0.969
             9     11       0.0       0.2080     0.0            1
             9     10       0.0       0.1100     0.0            1
             4     12       0.0       0.2560     0.0         0.932
            12     13       0.0       0.1400     0.0            1
            12     14       0.1231    0.2559     0.0            1
            12     15       0.0662    0.1304     0.0            1
            12     16       0.0945    0.1987     0.0            1
            14     15       0.2210    0.1997     0.0            1
            16     17       0.0824    0.1923     0.0            1
            15     18       0.1073    0.2185     0.0            1
            18     19       0.0639    0.1292     0.0            1
            19     20       0.0340    0.0680     0.0            1
            10     20       0.0936    0.2090     0.0            1
            10     17       0.0324    0.0845     0.0            1
            10     21       0.0348    0.0749     0.0            1
            10     22       0.0727    0.1499     0.0            1
            21     23       0.0116    0.0236     0.0            1
            15     23       0.1000    0.2020     0.0            1
            22     24       0.1150    0.1790     0.0            1
            23     24       0.1320    0.2700     0.0            1
            24     25       0.1885    0.3292     0.0            1
            25     26       0.2544    0.3800     0.0            1
            25     27       0.1093    0.2087     0.0            1
            28     27       0.0       0.3960     0.0         0.968
            27     29       0.2198    0.4153     0.0            1
            27     30       0.3202    0.6027     0.0            1
            29     30       0.2399    0.4533     0.0            1
             8     28       0.0636    0.2000     0.0214         1
             6     28       0.0169    0.0599     0.065          1 ];
>>
```

Table 4.2 Line data input

```
cost =

         0    2.0000    0.0075
         0    1.7500    0.0175
         0    1.0000    0.0625
         0    3.2500    0.0083
         0    3.0000    0.0250
         0    3.0000    0.0250


mwlimits =

    50   200
    20    80
    15    50
    10    35
    10    30
    12    40
```

Table 4.3 Cost coefficients and Active power limits input

4.4 MATLAB OUTPUTS

1. Ordinary NR load flow-

Power Flow Solution by Newton-Raphson Method
Maximum Power Mismatch = 2.79877e-009
No. of Iterations = 6

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar	Injected Mvar
1	1.060	0.000	0.000	0.000	56.890	30.371	0.000
2	1.043	-0.646	21.700	12.700	70.000	9.617	0.000
3	1.027	-2.100	2.400	1.200	0.000	0.000	0.000
4	1.019	-2.522	7.600	1.600	0.000	0.000	0.000
5	1.010	-3.237	64.200	19.000	45.000	7.859	0.000
6	1.014	-3.042	0.000	0.000	0.000	0.000	0.000
7	1.004	-3.656	22.800	10.900	0.000	0.000	0.000
8	1.010	-3.158	30.000	20.000	25.000	7.371	0.000
9	1.038	-3.730	0.000	0.000	0.000	0.000	0.000
10	1.022	-5.583	5.800	2.000	0.000	0.000	0.000
11	1.072	-1.052	0.000	0.000	25.000	17.888	0.000
12	1.054	-4.521	11.200	7.500	0.000	0.000	0.000
13	1.071	-2.034	0.000	0.000	35.000	13.578	0.000
14	1.036	-5.493	6.200	1.600	0.000	0.000	0.000
15	1.028	-5.592	8.200	2.500	0.000	0.000	0.000
16	1.033	-5.231	3.500	1.800	0.000	0.000	0.000
17	1.020	-5.687	9.000	5.800	0.000	0.000	0.000
18	1.014	-6.301	3.200	0.900	0.000	0.000	0.000
19	1.009	-6.529	9.500	3.400	0.000	0.000	0.000
20	1.011	-6.351	2.200	0.700	0.000	0.000	0.000
21	1.010	-6.100	17.500	11.200	0.000	0.000	0.000
22	1.013	-6.003	0.000	0.000	0.000	0.000	0.000
23	1.010	-6.102	3.200	1.600	0.000	0.000	0.000
24	1.000	-6.466	8.700	6.700	0.000	0.000	0.000
25	1.003	-6.864	0.000	0.000	0.000	0.000	0.000
26	0.985	-7.296	3.500	2.300	0.000	0.000	0.000
27	1.014	-6.833	0.000	0.000	0.000	0.000	0.000
28	1.011	-3.476	0.000	0.000	0.000	0.000	0.000
29	0.994	-8.086	2.400	0.900	0.000	0.000	0.000
30	0.983	-8.985	10.600	1.900	0.000	0.000	0.000
Total			253.400	116.200	256.890	86.684	0.000

Table 4.4 Ordinary load flow solution

```
B =

    0.0274    0.0111   -0.0009   -0.0008    0.0007    0.0039
    0.0111    0.0137    0.0010   -0.0016   -0.0005    0.0019
   -0.0009    0.0010    0.0204   -0.0075   -0.0072   -0.0057
   -0.0008   -0.0016   -0.0075    0.0145    0.0045    0.0027
    0.0007   -0.0005   -0.0072    0.0045    0.0128   -0.0007
    0.0039    0.0019   -0.0057    0.0027   -0.0007    0.0253


B0 =

    0.0023    0.0004   -0.0014    0.0012    0.0005    0.0035


B00 =

    0.0013

Total system loss = 3.49037 MW

Total generation cost =     830.58 $/h
Incremental cost of delivered power (system lambda) =  3.922082 $/MWh
Optimal Dispatch of Generation:

  108.3548
   57.4474
   23.2910
   35.0000
   18.2434
   16.9062

Absolute value of the slack bus real power mismatch, dpslack =   0.5146 pu
>>
```

Figure 4.2 MATLAB Command window output for ordinary load flow

2. Ordinary Newton Raphson Load flow followed by ELD analysis-

```
B =

    0.0218    0.0108    0.0000   -0.0009    0.0002    0.0030
    0.0108    0.0152    0.0014   -0.0016   -0.0006    0.0021
    0.0000    0.0014    0.0292   -0.0073   -0.0100   -0.0086
   -0.0009   -0.0016   -0.0073    0.0142    0.0046    0.0031
    0.0002   -0.0006   -0.0100    0.0046    0.0169   -0.0009
    0.0030    0.0021   -0.0086    0.0031   -0.0009    0.0402


B0 =

    0.0005    0.0012   -0.0023    0.0012    0.0005    0.0082


B00 =

    0.0013

Total system loss = 5.23295 MW
Incremental cost of delivered power (system lambda) =  3.897272 $/MWh
Optimal Dispatch of Generation:

  110.3755
   56.5174
   22.9754
   35.0000
   17.8282
   15.9384

Absolute value of the slack bus real power mismatch, dpslack =   0.0007 pu
                   Power Flow Solution by Newton-Raphson Method
                      Maximum Power Mismatch = 1.01118e-005
                             No. of Iterations = 2

    Bus  Voltage  Angle    ------Load------    ---Generation---   Injected
    No.  Mag.     Degree     MW       Mvar       MW       Mvar       Mvar

     1   1.060    0.000    0.000     0.000   110.308    16.443     0.000
     2   1.043   -1.913   21.700    12.700    56.532    20.221     0.000
```

3	1.025	-3.451	2.400	1.200	0.000	0.000	0.000
4	1.016	-4.202	7.600	1.600	0.000	0.000	0.000
5	1.010	-6.124	64.200	19.000	22.976	15.802	0.000
6	1.013	-4.877	0.000	0.000	0.000	0.000	0.000
7	1.004	-5.920	22.800	10.900	0.000	0.000	0.000
8	1.010	-4.804	30.000	20.000	35.000	8.507	0.000
9	1.038	-6.465	0.000	0.000	0.000	0.000	0.000
10	1.023	-8.374	5.800	2.000	0.000	0.000	0.000
11	1.072	-4.557	0.000	0.000	17.821	17.750	0.000
12	1.052	-7.915	11.200	7.500	0.000	0.000	0.000
13	1.071	-6.776	0.000	0.000	15.997	14.605	0.000
14	1.034	-8.781	6.200	1.600	0.000	0.000	0.000
15	1.027	-8.775	8.200	2.500	0.000	0.000	0.000
16	1.032	-8.377	3.500	1.800	0.000	0.000	0.000
17	1.020	-8.586	9.000	5.800	0.000	0.000	0.000
18	1.013	-9.349	3.200	0.900	0.000	0.000	0.000
19	1.008	-9.494	9.500	3.400	0.000	0.000	0.000
20	1.011	-9.272	2.200	0.700	0.000	0.000	0.000
21	1.010	-8.955	17.500	11.200	0.000	0.000	0.000
22	1.013	-8.750	0.000	0.000	0.000	0.000	0.000
23	1.010	-8.978	3.200	1.600	0.000	0.000	0.000
24	1.000	-9.155	8.700	6.700	0.000	0.000	0.000
25	1.004	-9.215	0.000	0.000	0.000	0.000	0.000
26	0.986	-9.646	3.500	2.300	0.000	0.000	0.000
27	1.015	-8.976	0.000	0.000	0.000	0.000	0.000
28	1.010	-5.309	0.000	0.000	0.000	0.000	0.000
29	0.995	-10.226	2.400	0.900	0.000	0.000	0.000
30	0.984	-11.124	10.600	1.900	0.000	0.000	0.000
Total			253.400	116.200	258.632	93.328	0.000

```
Total generation cost =     762.46 $/h
>>
```

Figure 4.3 MATLAB Command window output for ordinary load flow followed by ELD

3. Distributed slack bus model using ELD analysis-

```
B =

    0.0218    0.0108   -0.0003   -0.0009    0.0002    0.0030
    0.0108    0.0147    0.0010   -0.0015   -0.0006    0.0020
   -0.0003    0.0010    0.0219   -0.0071   -0.0085   -0.0073
   -0.0009   -0.0015   -0.0071    0.0138    0.0044    0.0029
    0.0002   -0.0006   -0.0085    0.0044    0.0169   -0.0009
    0.0030    0.0020   -0.0073    0.0029   -0.0009    0.0404


B0 =

    0.0005    0.0011   -0.0017    0.0010    0.0005    0.0082


B00 =

    0.0013

Total system loss = 5.21046 MW
Incremental cost of delivered power (system lambda) =  3.895488 $/MWh
Optimal Dispatch of Generation:

  110.3242
   56.5787
   23.0527
   35.0000
   17.7430
   15.8665

Absolute value of the slack bus real power mismatch, dpslack =   0.0000 pu
                   Power Flow Solution by Newton-Raphson Method
                      Maximum Power Mismatch = 1.14877e-005
                             No. of Iterations = 2

    Bus  Voltage  Angle    ------Load------    ---Generation---   Injected
    No.  Mag.     Degree     MW       Mvar       MW       Mvar       Mvar
```

1	1.060	0.000	0.000	0.000	110.326	16.447	0.000
2	1.043	-1.913	21.700	12.700	65.149	20.215	0.000
3	1.025	-3.453	2.400	1.200	0.000	0.000	0.000
4	1.016	-4.205	7.600	1.600	0.000	0.000	0.000
5	1.010	-6.121	64.200	19.000	48.385	15.781	0.000
6	1.013	-4.880	0.000	0.000	0.000	0.000	0.000
7	1.004	-5.921	22.800	10.900	0.000	0.000	0.000
8	1.010	-4.808	30.000	20.000	46.839	8.534	0.000
9	1.038	-6.475	0.000	0.000	0.000	0.000	0.000
10	1.023	-8.384	5.800	2.000	0.000	0.000	0.000
11	1.072	-4.576	0.000	0.000	17.739	17.750	0.000
12	1.052	-7.925	11.200	7.500	0.000	0.000	0.000
13	1.071	-6.790	0.000	0.000	15.934	14.611	0.000
14	1.034	-8.791	6.200	1.600	0.000	0.000	0.000
15	1.027	-8.784	8.200	2.500	0.000	0.000	0.000
16	1.032	-8.387	3.500	1.800	0.000	0.000	0.000
17	1.020	-8.596	9.000	5.800	0.000	0.000	0.000
18	1.013	-9.358	3.200	0.900	0.000	0.000	0.000
19	1.008	-9.503	9.500	3.400	0.000	0.000	0.000
20	1.011	-9.281	2.200	0.700	0.000	0.000	0.000
21	1.010	-8.964	17.500	11.200	0.000	0.000	0.000
22	1.013	-8.759	0.000	0.000	0.000	0.000	0.000
23	1.010	-8.987	3.200	1.600	0.000	0.000	0.000
24	1.000	-9.163	8.700	6.700	0.000	0.000	0.000
25	1.004	-9.221	0.000	0.000	0.000	0.000	0.000
26	0.986	-9.652	3.500	2.300	0.000	0.000	0.000
27	1.015	-8.982	0.000	0.000	0.000	0.000	0.000
28	1.010	-5.312	0.000	0.000	0.000	0.000	0.000
29	0.995	-10.231	2.400	0.900	0.000	0.000	0.000
30	0.984	-11.129	10.600	1.900	0.000	0.000	0.000
Total			253.400	116.200	304.371	93.337	0.000

```
Total generation cost =     762.19 $/h
>>
```

Figure 4.4 MATLAB Command window output for distributed slack bus model using ELD analysis

Table 5.1 Comparison of the results of IEEE 30 bus system

	Ordinary NR load flow method	NR load flow using ELD scheme	Distributed slack bus model with ELD
Total System Loss	3.49037 MW	5.23295 MW	5.21046 MW
Incremental cost of delivered power (λ)	3.922082 $/MWh	3.897272 $/MWh	3.895488 $/MWh
Total Generation Cost	830.58 $/h	762.46 $/h	762.19 $/h

From the above comparison we extract the following information:

By using ELD scheme we save 68.12 $/h as compared to the ordinary NR load flow method which is equivalent to saving 0.6 million $ per annum. But by using the Distributed slack bus model approach we further save 0.27 $/h which turns out to be approximately 2300 $ per annum. The line losses are almost the same as compared to that of ELD scheme. Thus it is all about saving capital while distributing the power optimally or qualitatively.

Chapter 5

Conclusion

5. CONCLUSION

The distributed slack bus model for ELD analysis can serve as an important tool for reducing generation costs (although by a small margin) and improving the optimal power distribution. However, it may have a small impact on the total system losses. The annual savings in generation cost keeps on increasing with the increase in number of generating units attached to the system thus making the load dispatch more and more economic. Hence the proposed method should be analyzed and introduced into practical network systems in order to reduce the overall cost of generation. This project can be modified in future with different structure of Participation Factor usage in the Newton Raphson matrix in order to further aid the cause of reducing the cost of generation.

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